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The impact of rapid coastline changes and sea level rise on the tides in the Bohai Sea, China

H. E. Pelling,^{1,2} K. Uehara,¹ and J. A. M. Green²

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[1] The tidal regime in the Bohai Sea, China, is investigated using observations and an established numerical tidal model. The area has recently experienced rapid coastline changes due to natural developments of the Yellow River delta and large-scale anthropogenic land reclamation. These morphological changes are not reflected in most global bathymetric databases and are thus rarely incorporated into investigations of the Bohai Sea. It is shown that there have indeed been significant changes in the tidal regime in the Bohai Sea over the last 35 years, with M_2 amplitudes changing up to 20 cm in some parts. The model captures some of these changes when the appropriate bathymetries are used. Furthermore, the simulations show that the tides in the Bohai Sea have become more sensitive to future sea level rise and the way in which it is implemented in the model (i.e., whether or not flood defenses are included). These sensitivity changes are due to the recent coastal developments.

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1. Introduction

[2] It has been suggested that sea level will rise with 0.18–0.79 m over the present century [Meehl *et al.*, 2007], although larger changes cannot be excluded [e.g., Rahmstorf, 2007; Vermeer and Rahmstorf, 2009]. Recent studies show that sea level changes may affect regional tidal dynamics in shelf seas [Pickering *et al.*, 2012; Ward *et al.*, 2012], although in order to evaluate the models' responses, extreme levels of sea-level rise were required. Global long-term tide-gauge data show some changes in the tides with observed sea-level rise (SLR) [Flick *et al.*, 2003; Ray, 2006, 2009; Jay, 2009; Woodworth, 2010], but these changes are poorly captured by global tidal models due to the coarse resolution of the models [Green, 2010; Müller *et al.*, 2011]. In the Bohai Sea (Figure 1), however, significant land reclamation along the coast has led to large-scale changes in the tidal amplitudes within the basin [Zhang and Wang, 1999; Li *et al.*, 2011]. Here, we aim to investigate whether an estab-

lished tidal model can capture these changes, and how the tides in the Bohai Sea may change with future SLR.

[3] From a relatively coarse global simulation, Green [2010] suggested that even with 5 m SLR there are only minor impacts on the global tidal dissipation. Müller *et al.* [2011] suggested that there have been significant global changes in the tides related to SLR over the last century, but that global tidal models struggle to reproduce these changes due to coarse resolution. One would guess, however, that regional high-resolution simulations could be able to capture observed changes in long-term tidal amplitudes. One issue is that even for the same area—the European Shelf—different studies show quantitatively similar but qualitatively very different results [e.g., Pickering *et al.*, 2012; Ward *et al.*, 2012]. These discrepancies have been explained by the way SLR is implemented in the models [Pelling *et al.*, 2013; Pelling and Green, 2013]: when vertical walls are introduced at the present day coastline the tides respond differently to an increased sea level compared to when land is allowed to flood and new wet grid cells are formed within the model domain. In the first case, the changes are mainly due to (minor) modifications of the propagation properties of the tidal wave. The response to the second case, when land is allowed to flood, has a more complicated dynamic explanation that depends on a combination of altered propagation properties and a shift of some of the tidal dissipation to the newly formed ocean areas.

[4] The Bohai Sea (Figure 1) is a semienclosed sea situated in northeast China and may be described as a hotspot among the world's marginal seas with respect to its large natural and anthropogenic coastline changes. Most striking is the shift of the river mouth of the Yellow River, which commenced in 1976. This has led to the Yellow River Delta reforming as a spit-like feature extending as far as 20 km into the southern part of the sea—a feature that did not exist before 1976. Other human activities along the western

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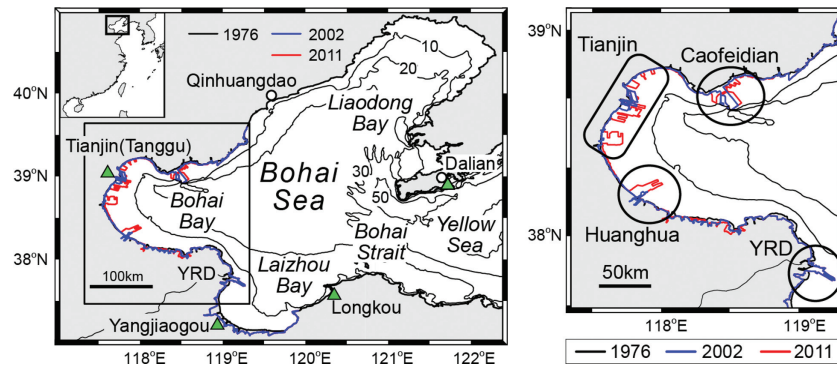


Figure 1. The 1976 bathymetry of the Bohai Sea and a close-up view of the Bohai Bay. Coastlines from the 2002 (blue) and 2011 (red) bathymetry are also shown along with the location of long-term tidal gauge stations (green triangles).

coast have resulted in the reclamation of 700 km² of land in the last decade, an area comparable to that of Singapore. Furthermore, seawalls have been constructed along the coastlines in recent years to protect coastal areas, many of which are either urbanized or developed as aquaculture and saltpan ponds. These changes in the coastline are not reflected in recent numerical models of the Bohai Sea. This is partly because the major digital bathymetries, e.g., GEBCO [Jakobsson *et al.*, 2008], usually follow the coastline prior to 1976. More recent bathymetries provide us with a unique opportunity to investigate if we can relate the observed changes in the tides in the Bohai Sea to the changes in topography, and if a numerical tidal model can reproduce the response of the tides. The investigation uses observations from tide gauges together with an established numerical tidal model, which has been used several times for investigations of other shelf seas [Uehara and Saito, 2003; Uehara *et al.*, 2006; Ward *et al.*, 2012; Pelling *et al.*, 2013].

[5] This paper continues with a more detailed description of the Bohai Sea and the data and model used (section 2). This is followed by the results of the different simulations in section 3 and a discussion in section 4.

2. Data and Modeling

2.1. The Bohai Sea

[6] The Bohai Sea forms the northernmost part of the East China Sea continental shelf and is connected to the Yellow Sea through the Bohai Strait in the east (Figure 1). It is close to megacities such as Beijing and Tianjin and embraces major oil fields and is consequently home to vast shipping and offshore activities. The Bohai Sea is comprised of three bays: Bohai Bay, Laizhou Bay, and Liaodong Bay located in the west, south, and northeast, respectively. The Yellow River drains into the southwestern basin, and discharges some 207.47×10^8 m³ yr⁻¹ of water and 4.63×10^8 m³ yr⁻¹ of sediment [Yu *et al.*, 2011], making it the world's largest supplier of fluvial sediment to the ocean.

[7] Between 1976 and 2002, coastline changes in the Bohai Sea were mainly associated with motions of the Yellow River delta. The shift of the Yellow River mouth in 1976 resulted in the formation of a spit-like feature that extended 20 km eastward into Laizhou Bay, whereas parts

of the northern coast of the delta were eroded due to the shift in the sediment supply [Chu *et al.*, 2006]. Erosion was also observed along the western and southern coasts of Laizhou Bay [Feng *et al.*, 2006]. In addition, major land reclamations took place in the Tianjin, Huanghua, and Caofeidian areas within Bohai Bay in the late 1990s, and more extensive work has been carried out after 2006. This has led to the coastline moving up to 20 km seaward from its 1990 position.

2.2. Tides in the Bohai Sea

[8] The tides in the Bohai Sea are relatively small and fall into the microtidal/mixed-semidiurnal category, although they still play a significant role in the dynamics of the area [Zhu and Chang, 2000; Wang *et al.*, 2007]. Knowledge of tidal elevations in the Bohai Sea, especially those of coastal zones in Bohai Bay and Laizhou Bay, is essential when assessing coastal vulnerability to flooding, because the area is subject to frequent storm surges, the propagation of which is highly dependent on the state of the tide [Li *et al.*, 2010].

[9] Long-term tidal gauge data from the Bohai Sea is sparse, but we have been able to obtain data from a variety of sources (see Table 1). Annual M_2 and S_2 amplitudes and phases from Yangjiaogu and Longkou (located at either side of Laizhou Bay) were obtained from Zhang and Wang [2000], whereas M_2 amplitude and phase data from the Tanggu (Tianjin) tidal gauge station was extracted from Li *et al.* [2011]. Hourly tide gauge data were available from the Dalian and Laohutan tide gauges from the University of Hawaii sea level centre (UHSLC). These two data sets cover two different time periods but after 1980 they are located in the same position. The data sets have therefore been merged (data after 1980) and are treated as one. The tidal characteristics were obtained using harmonic analysis through the TASK software [Bell *et al.*, 2002]. The analysis was conducted on yearly blocks of data covering the period 1980–1997.

[10] Present day constituent information was obtained from the 10 ports listed in the year 2000 version of the Admiralty Tide Tables frequently used for navigation. We had also planned to use the Oregon State Tidal Inversion System (OTIS) ATLAS (hereafter referred to as ATLAS) regional tidal inversion solutions available online (<http://volkov.oce.orst.edu/tides/YS.html>), but it became apparent that these use pre-reclamation bathymetry with altimetry

Table 1. Summary of Long-Term Tidal Gauge Station Data Used in the Analysis Period^a

Station	Position	Period of Observation	Type of Observation	Source
Tanggu (Tianjin)	38°59 N, 117°47 E	1958–2008	Annual amplitudes	<i>Li et al.</i> [2011]
Dalian/Laohutan	38°52 N, 121°41E	1980–1997	Hourly sea-level data	UHSLC
Yangjiaogou	37°16 N, 118°57 E	1952–1994	Annual amplitudes	<i>Zhang and Wang</i> [1999]
Longkou	37°38 N, 120°20 E	1952–1990	Annual amplitudes	<i>Zhang and Wang</i> [1999]

^aLocations are shown by green triangles in Figure 1.

data, which is an average over the last 19 years. Consequently, there are some inconsistencies in the regional solutions for the ATLAS, especially in relation to the tide-gauge data in the north of Liaodong Bay (Figure 2a), and we opted not to use it as a validation tool.

2.3. Modeling the Bohai Sea

2.3.1. Model Bathymetry

[11] For our modeling purposes, three bathymetries are used, representing the conditions at three different time slices over the last 35 years. Depths in the first bathymetric dataset were derived from current U.S. navigational charts, which in turn are based on Chinese charts of data collected up to 1976 (hereafter referred to as the “1976” bathymetry). The second data set uses Chinese charts published in 2008. This data set, hereafter called “2002,” contains new depth data measured in 2002 in Laizhou Bay and data sampled until 2006 for parts of Bohai Bay. In the third data set, the bathymetry in Bohai Bay was replaced with new Chinese charts issued by 2011 and some of the coastlines were updated by using satellite images from November 2011. Consequently, we refer to this data set as the “2011” bathymetry in the following. Note that all three data sets use the same depth data for the Liaodong Bay and the Bohai Strait areas west of 120.5°E and north of 39.5°N. This is partly because the coastline changes in these areas have been relatively small, but mainly because more recent soundings are not available for Liaodong Bay. All depths obtained from navigational charts were raised by 1 m to convert the low-tide datum into a mean sea level, based on mean sea levels at standard ports in the Bohai Sea listed in Chinese Tide Table (2012 edition).

2.3.2. Tidal Model

[12] Tides were predicted using the Kyushu University Tidal Model (KUTM; see *Uehara et al.* [2006] for a detailed description)—a two-dimensional finite-difference tidal model, set up with a spatial resolution of 1/60 degree for the domain shown in Figure 2b. The model solves the Navier-Stokes shallow water equations for surface elevation (η) and depth-averaged current vector (\mathbf{u}):

$$\frac{\partial \mathbf{Du}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{Du} + \mathbf{k}(2\Omega \sin \varphi) \times \mathbf{Du} = -gD\nabla(\eta - \eta_e) - C_d|\mathbf{u}|\mathbf{u} + A_h D \nabla^2 \mathbf{u} \quad (1)$$

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (D\mathbf{u}) = 0 \quad (2)$$

where t is time, ∇ is the horizontal gradient operator, $D = H + \eta$, where H is the water depth. Ω is the angular velocity of the Earth’s rotation, φ is the latitude, \mathbf{k} the vertical unit vector, g is the gravitational constant, η_e the tide gener-

ating potential, and $A_h = 100 \text{ m}^2/\text{s}$ is the horizontal eddy viscosity. Energy is lost through a standard quadratic bed friction parameterization with a drag coefficient (C_d) tuned to 0.0015 to minimize the discrepancy with the tide-gauge data. This value is on the low side compared to studies of different regions [e.g., *Pelling et al.*, 2013], but it is similar to those adopted in regional models focused on Bohai Sea tides [e.g., *Lu and Zhang*, 2006]. The discrepancy can be explained by the smoothness of the seabed and it should be noted that using different values of the drag coefficient did not qualitatively affect the result of this study.

[13] The forcing consisted of the astronomic tidal potential, applied over the entire domain, and tidal elevations specified on open boundaries along 122.4°E meridian. The latter were derived from the TPXO7.2 database (see *Egbert and Erofeeva* [2002] for details and <http://volkov.oce.orst.edu/tides/global.html> for the latest version). Simulations were made for the M_2 , S_2 , K_1 , O_1 , and N_2 constituents, with M_4 being an additional part of the output, although the focus here is exclusively on the M_2 as it dominates the tidal dynamics.

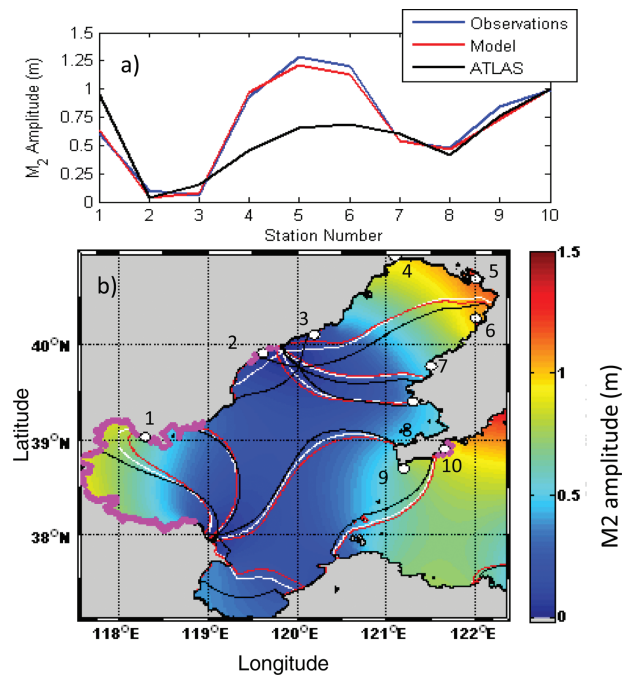


Figure 2. (a) Comparison of observed and modeled M_2 amplitudes at positions shown in Figure 2b. (b) Modeled M_2 amplitudes and phase lines (white) for the 2011 bathymetry along with the spring (black) and neap (red) phase lines (see the text for details). The position of simulated flood defenses is shown by the magenta line.

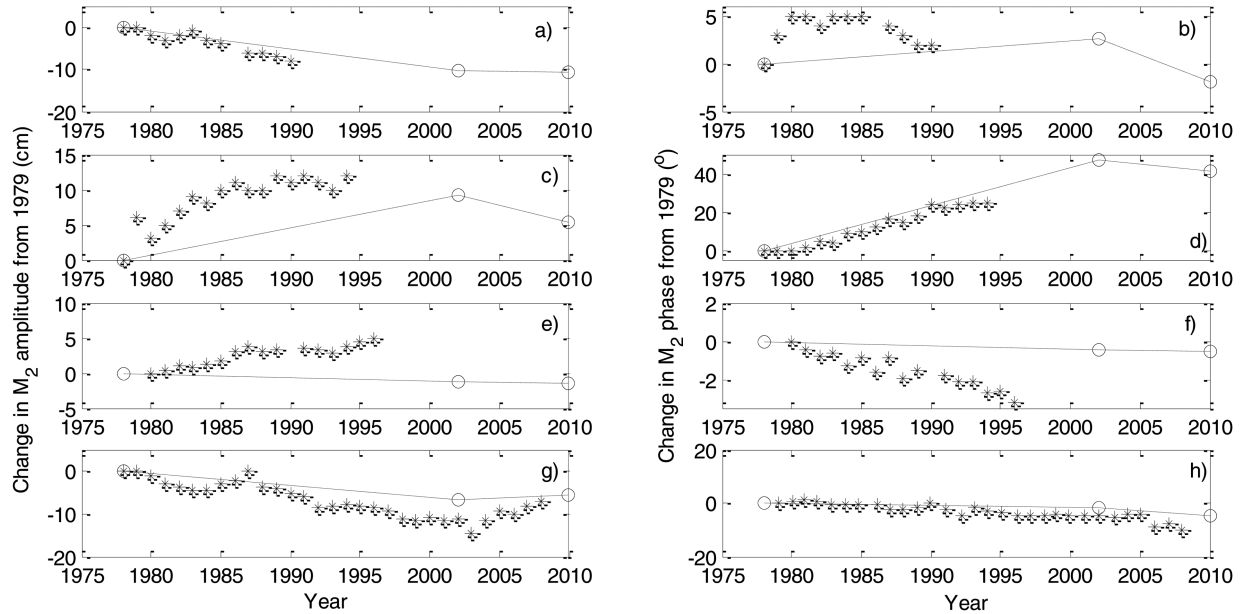


Figure 3. Comparison of modeled (black line) and tide gauge (stars) (a, c, e, and g) amplitudes and (b, d, f, and h) phases from stations at Longkou (Figures 3a and 3b), Yangjiaogou (Figures 3c and 3d), Dalian/Laohutan (Figures 3e and 3f), and Tianjin (Figures 3g and 3h). See the green triangles in Figure 1 for locations.

2.3.3. Numerical Experiments

[14] A series of numerical runs were conducted by using the three different model bathymetries described above, i.e., covering the years 1976, 2002, and 2011 (the 2011 bathymetry is henceforth taken to be the present state when we discuss future SLR). Further runs were done using the 1976 and 2011 bathymetries but adding a (future) SLR of 1, 2, or 3 m. Regardless of scenario, the model was run for 45 days, of which the last 29.5 were used for harmonic analysis to obtain tidal elevations and velocities, and their respective phases for each constituent.

[15] In the SLR simulations, we use three different methods to implement the change in sea level. In the first case, we allowed the inundation of lands and the expansion of the sea (called the “flood” case in the following). The second method introduced vertical walls along the original coastline and then raised the sea level (this is the “no-flood” case in Pelling et al. [2013] and Pelling and Green [2013]), whereas in the third case, we only added the vertical walls around Bohai Bay and the coastline near the cities of Qinhuangdao and Dalian (Figure 2; location of cites shown in Figure 1) to simulate the effect of flood defenses near urbanized areas (we henceforth refer to this as the “partial flood” case).

3. Results

3.1. Model Validation

[16] The model simulations (and observations) show that the (M_2) tides in the Bohai Sea are quite weak, with a spatially averaged amplitude of 0.49 m and a maximum, found in northern Liaodong Bay, of 1.4 m (Figure 2b). Comparing the model to the observed values listed in Admiralty Tide Tables, it becomes evident that the model captured the tidal amplitudes in the area well (and that the OTIS regional inversion simulation discussed before has some issues; cf.

Figure 2a). This is supported by the root-mean-square error (RMSE) between the model and the Admiralty data, which achieve 0.05 m for the M_2 constituent. Furthermore, we also calculated the variance captured defined as: $VC = 100 \times \left[1 - \left(\frac{RMS}{S} \right)^2 \right]$, where s is the root mean square of the observed amplitudes and RMS is the root mean squared difference between the model and the observations mentioned above. The modeled M_2 amplitudes achieved a variance captured of 99.5%. These agreements give us confidence in the signals reported on later.

[17] Two amphidromic points are evident in Figure 2b, both of which are degenerate. The first is close to the city of Qinhuangdao, whereas the second can be found inland between the Bohai and Laizhou Bays. The location of the latter point is supported in observations [e.g., Fang, 1986], but whether the amphidromic point near Qinhuangdao is degenerate or real has been the cause for some debate [e.g., Fang, 1986; Fang et al., 2004; Yao et al., 2012]. In an attempt to solve the dispute, we investigate the spring-neap cycle by comparing the $M_2 + S_2$ and $M_2 - S_2$ response (this is the only time we do not solely discuss M_2 in the paper). The result is quite clear (see Figure 2b) and shows that the amphidromic point is real during spring tides and degenerates as we move toward neaps, lending support to both sides of the dispute.

3.2. Effects of Past Land Reclamation on Tidal Amplitudes

3.2.1. The 1976 and 2002 Cases

[18] The simulations for our three different bathymetries, which can be interpreted as a simulation of the decadal changes of the tides in the Bohai Sea, were compared to data from the long-term tide gauge stations listed in Table 1, and are shown in Figure 3. With the exception of the tidal

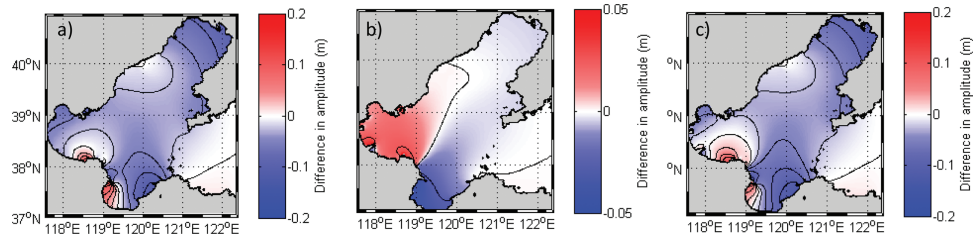


Figure 4. Evolution of M_2 amplitude using the different bathymetries. (a) The change in tides between the 1976 and 2002 cases shown as 2002 minus 1976—this approach is used whenever we are looking at a difference. (b) The change in tides between the 2002 and 2011 cases (note the different axis limits). (c) The change in tidal amplitude between the 1976 and 2011 cases. Here, amplitude contour lines are added at an interval of 0.025 m.

phase at Longkou and amplitude at Dalian/Laohutan (Figures 3b and 3e), the trends in both observed and modeled tides are going in the same direction, but the amplitudes of the trends do not necessarily correlate. There are several possible reasons for this discrepancy, with the model accuracy being the most obvious. This could be due to inaccurate bathymetries or to the omission of a significant process not identified here. Another possibility is that we have not been able to remove or correct for the 18.61 year nodal cycle [e.g., Gratiot et al., 2008] due to the observational records being short. However, Haigh et al. [2011] have modeled the global influence of the 18.61 year cycle and estimated a range for it of approximately 7 cm in the Bohai Sea. This is smaller than the observed signal, suggesting that the 18.61 year cycle cannot be the only process we are missing. Despite this, the model does a good job and we are confident in its ability.

[19] When comparing the model simulations in more detail, we see that between 1976 and 2002 the modeled amplitudes changed by more than 5 cm throughout the domain (Figure 4a). In Laizhou Bay, the model indicated an amplitude increase by more than 20 cm in the western part, but decreases by up to 10 cm in the eastern part of the Bay. This is consistent with tide-gauge records analyzed by Zhang and Wang [2000] (see Figure 3), in which the observed M_2 tides increased by some 20 cm at Yangjiaogou Station in southwest Laizhou Bay during 1975–1990, whereas it weakened by 9 cm between 1980 and 1994 at Longkou Station in the northeastern part of the Bay. These changes—seen in both the model and observations—are most likely due to a reversal of the propagation of the tidal wave: it traveled anticlockwise in the 1976 case, whereas it proceeded in a clockwise direction in the 2002 case. The reason for this reversal is the change of the Yellow River Delta after 1976, forcing the tidal wave to move around the spit-like feature of the Delta in the 2002 simulation. Our model results also indicate an overall weakening of the M_2 amplitude of up to 7 cm in Bohai Bay, except around the northern coast of the Yellow River delta. This decreasing trend is supported by the tide-gauge record from Tanggu in the western Bohai Bay [Li et al., 2011]. The M_2 amplitude also decreased by more than 8 cm at the head of Liaodong Bay between the 1976 and 2002 simulations.

[20] The present results again highlight that shelf sea tides are extremely sensitive to bathymetric perturbations [e.g., Pelling et al., 2013], but they also point out that other processes may affect the decadal trend of tides in the Bohai Sea.

[21] Zhang and Wang [2000] simulated the M_2 tides in the Bohai Sea for the years 1934, 1959, and 1989. Their simulated amplitude differences in the Bohai and Liaodong Bays between 1959 and 1989 are similar to the present ones, but their amplitudes in eastern Laizhou Bay are opposite to those observed at Longkou Station. This discrepancy may have been caused by an insufficient spatial resolution around the Yellow River delta in the older databases used by Zhang and Wang [2000].

3.2.2. The 2002 and 2011 Cases

[22] The modeled changes in the M_2 amplitude between 2002 and 2011 (Figure 4b) are smaller than those seen between the 1976 and 2002 simulations, and they are restricted to the Bohai Bay and Laizhou Bay. In Laizhou Bay, the tidal amplitudes decrease throughout the Bay between the 2002 and 2011 simulations, whereas the changes have the opposite sign in the Bohai Bay. This is consistent with the observations at Tianjin, where the M_2 amplitude trend changed sign, from negative to positive, between 2000 and 2003 (see Figure 3g and Li et al. [2011]). Because the largest difference between the 2002 and 2011 bathymetries is in the extent of the reclaimed land in Bohai Bay, it is suggested that the enhancement of the tidal amplitudes observed in Bohai Bay over this period is due to the extensive changes in the coastline over the last decade.

3.3. Currents and a Dynamic Explanation

[23] There is an increased current speed in the southern part of Laizhou Bay between the 1976 and 2002 simulations (Figure 5a). This is due to the projection of the Yellow River Delta, which has modified the tidal current, leading to a retreat due to erosion of the coastline in the Laizhou Bay. This is in contrast to the impact of the other coastal changes in Laizhou Bay between 2002 and 2011, where the model suggests that the changes are confined to nearshore areas (Figure 5c). Increased tidal currents along sections between Tanggu and Huanghua may therefore have caused coastal erosion there. Over the entire period (i.e., comparing 1976 and 2011), the tidal currents are generally reduced in Bohai Bay, with the largest change being a decrease of 0.47 m s^{-1} near the northeastern coast (Figure 5e). However, the position of the maximum tidal current, which occurs just southeast of the end of Liaodong Peninsula, does not change between the different scenarios.

[24] The change in bed stress and tidal energy dissipation is closely linked to changes in tidal velocity, as tidal dissipation (ε) and bed shear stress (τ) are calculated as

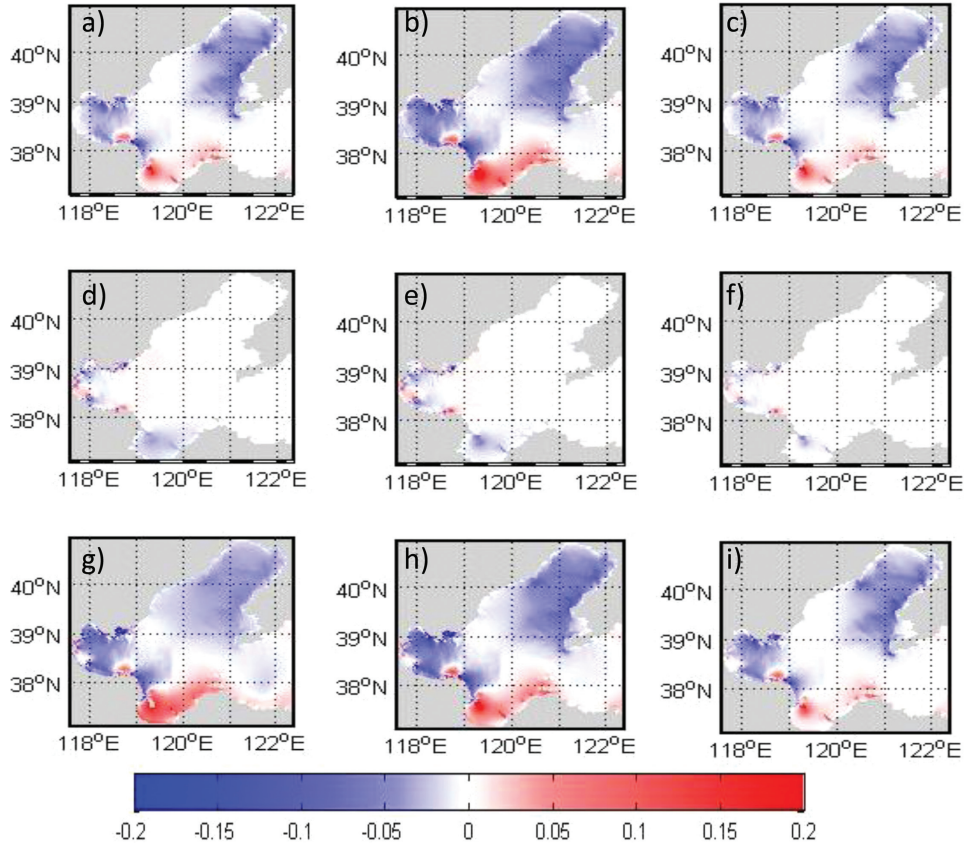


Figure 5. Modeled differences in M_2 tidal current speed, bed stress, and tidal dissipation rates between (a–c) 1976 and 2002, (d–f) 2002 and 2011, and (g–i) 1976 and 2011 cases. Figures 5a, 5d, and 5g show tidal velocities (m s^{-1}), Figures 5b, 5e, and 5h show the tidal bed stress (N m^{-2}), and Figures 5c, 5f, and 5i show the tidal energy dissipation (W m^{-2}). Please note the different units between columns.

$$\varepsilon = \rho C_d |u|^3 \quad (3)$$

and

$$\tau = \rho C_d |u|^2 \quad (4)$$

where ρ is the reference density (1024 kg m^{-3}) and u is the absolute tidal velocities simulated by the model. The largest change in dissipation is found where we see the largest change in tidal current speed (i.e., near the northeastern coast of Bohai Bay). However, there is a general decrease in bed shear stress over the whole region, except in Laizhou Bay. This suggests potential changes in the sediment transport capacity of the area, which is mainly controlled by the tides [Liu *et al.*, 1998]. In fact, the general direction of sediment transport is in the same direction as the residual tidal currents [Liu *et al.*, 1998], and the weak tidal currents throughout most of Laizhou Bay suggest a deposition regime dominated by fine sediments. The reduction in tidal bed shear stress over the north of Bohai Bay could thus result in a reduction in the capacity of the water column to erode and transport benthic sediment. However, strong erosion does occur in the Laotieshan Channel of the North Bohai Strait, where there is a maximum in tidal current velocity and an associated tidal scour furrow with highly sorted coarse sediments [Liu and Xia, 2004]. Although our

results do not suggest a transition of the Laotieshan Channel from erosion to deposition between our cases, it is possible that the quantity of sediment available for deposition in Liaodong Bay could be affected by these changes. Conversely, an increased tidal bed shear stress in Laizhou Bay may lead to less deposition of fine sediments, which in turn may lead to an increased turbidity of the water column, reducing the light penetration with associated ecological impacts.

[25] These results show that the extensive natural and anthropogenic land reclamation has indeed led to significant changes in the M_2 tidal amplitude throughout the Bohai Sea. The pattern of co-phase lines in Figure 2b indicates that the tide in the Bohai Sea first enters Liaodong Bay, then travels anticlockwise around Bohai and Laizhou Bays and finally, exits back through the strait. When the Yellow River Delta projects into Laizhou Bay, the delta acts to cut off the southeastern portion of the basin, resulting in larger tides in that area. The projection also shortens the path of the tidal wave. The coastal developments that took place between 2002 and 2011 in the Bohai Bay have had a similar impact in the model results. This also explains why there is no change in the position of maximum current, which is in the Bohai Bay and Bohai Bay is strongly influenced by the tides from the Yellow Sea (i.e., outside the basin).

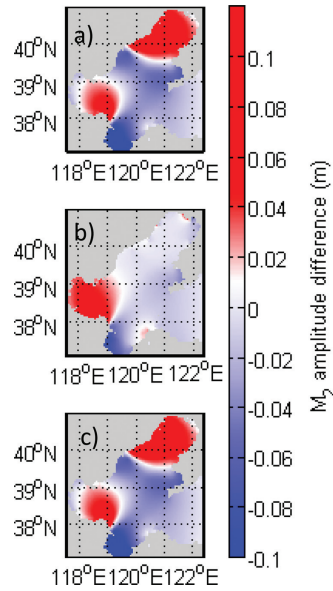


Figure 6. Impact on the tidal amplitude by 2 m SLR applied to the 2011 bathymetry. (a) The flood run, (b) the no-flood run, and (c) the partial flood simulations (see text and Figure 2 for details).

3.5. Future Scenarios

3.5.1. Response to SLR

[26] The simulated impact of 2 m SLR applied to the 2011 bathymetry is shown in Figure 6 for the three different implementation scenarios (e.g., flood, no flood, and partial flood). We again see that the response of the tides to SLR varied with the implementation method, but we also see large variation between each basin for each SLR case. For example, in the 2 m flood case, Liaodong Bay and the eastern part of Bohai Bay experience increased tidal amplitudes, whereas Laizhou Bay in the south experiences decreased tidal amplitudes (Figure 6a). This response is generally larger with flooding than without, again with the main differences found in the Liaodong and Bohai Bays. However, there are only very small differences in the tidal response between the flood and partial flood runs (Figures 6a and 6c), which suggests that the response of the Bohai Sea to SLR is controlled in regions further away from where flood defenses have been placed in the simulation.

[27] Further simulations with 1 and 3 m SLR show that the change in tidal amplitudes is not proportional to the level of SLR, regardless of implementation method (Figure 7). This is especially clear between the flood and no-flood simulations, whereas the flood and partial flood runs are virtually identical until after 2 m SLR. This is

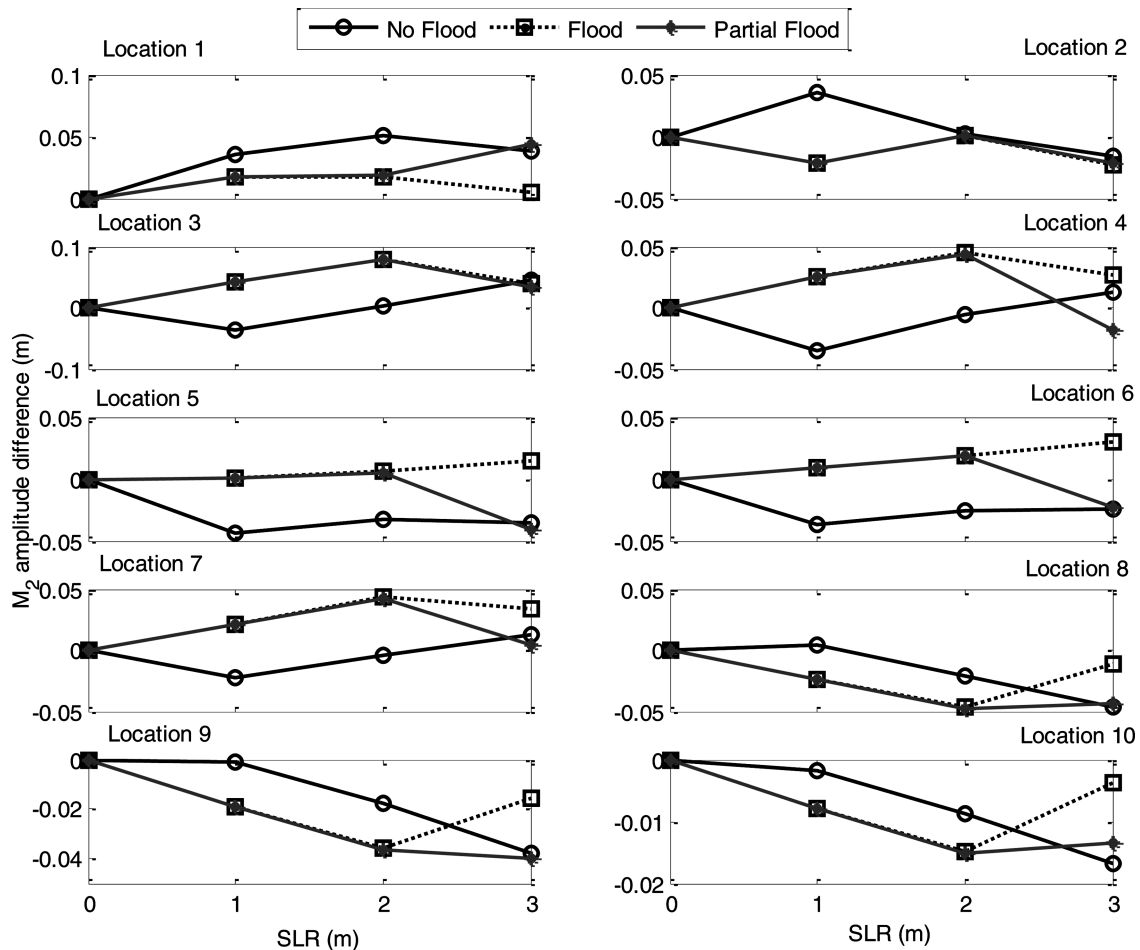


Figure 7. Response curves of the M_2 tidal amplitude to SLR for the locations shown in Figure 2b.

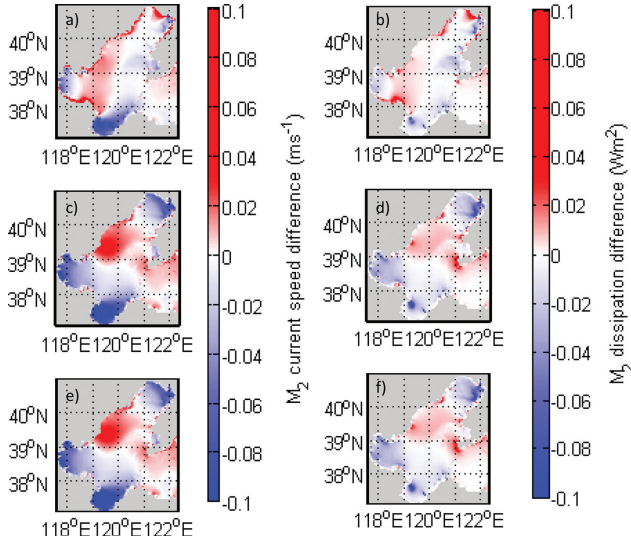


Figure 8. Effect of a 2 m SLR on the (a, c, and e) M_2 tidal current speed and (b, d, and f) tidal energy dissipation. Figures 8a and 8b show the results for the flood run, Figures 8c and 8d show the no-flood run, and Figures 8e and 8f show the results for the partial flood run.

most likely due to the flooding of the newly reclaimed land, which tends to have a topographic height of 2–3 m in the database, becoming inundated and hence floods.

[28] The changes in tidal amplitudes act to change to tidal currents as well (Figure 8). Again, the flood and partial flood runs show quite similar responses, and for a SLR of 2 m, all three scenarios predict significantly reduced current speeds and associated energy dissipation in Laizhou Bay. However, the simulation with 2 m SLR and flooding suggest that there are only small changes in the interior of the Bohai Sea, but large increases around the coastlines of Liaodong and Bohai Bays. The no-flood and partial flooding cases, on the other hand, show decreases in the Liaodong, Bohai, and Laizhou Bays and an increase in the inner part of the domain.

[29] These overall decreased tidal currents in Laizhou Bay suggest that the area would move to a generally less tidally energetic regime with large levels of future SLR. This is further supported by horizontally integrating the tidal energy dissipation over the domain. In the 2011 case, this amounts to 168 GW, with a very slight decrease for the

2 m SLR no-flood simulation (165 GW). However, with flooding—both partial and for the whole domain—the dissipation drops to 156 GW when integrated, implying potential for very significant change in the Bohai Sea with future SLR.

[30] In the no-flood and partial flood simulations, the decrease in tidal current speed and dissipation the Liaodong Bay is associated with an increase in tidal amplitude, but there are other areas in the Bohai Sea where we see enhanced amplitudes and reduced currents. We have therefore plotted, in Figure 9, the change of the horizontal gradient of the tidal elevation between 2011 and the 2 m SLR simulation. With 2 m SLR and no or partial flooding, the elevation gradient decreases because the tidal elevation decreases, but there is no difference in the elevation in the flood run. This suggests that there are different mechanisms controlling the response in Liaodong Bay, which sees a change in elevation gradient between the simulations, and in the southern part of the Bohai Sea, where changes in the spatial distribution of tidal energy dominate the response.

[31] We also conducted SLR runs on the 1976 bathymetry with the purpose to investigate if the Bohai Sea has become more sensitive to SLR. Figure 10 shows that the impact of 2 m SLR on the tides between the 1976 and the 2011 bathymetry. In fact, the spatially averaged absolute change in modeled tidal amplitude increases from 0.01 to 0.02 m for the no-flood runs, but decreases from 0.04 to 0.03 m for the flood and partial flood runs. These results suggest that the coastal developments have made the tides in the Bohai Sea more sensitive to future SLR, regardless of whether or not flood defenses are built.

3.5.2. Future Reclamation Scenarios

[32] Observations show that the Yellow River Delta is currently sinking [Syvitski et al., 2009], and we therefore performed a simulation where it was removed. This was achieved by setting the water depth of the area covered by the delta to 2 m and interpolating the water depth at the edges to smooth the transition. It is also likely that land reclamation will continue as the Chinese economy continues to grow, and further simulations were done where the rate of land reclamation between 2002 and 2011 in the Bohai Bay was extrapolated 100 years into the future. We also conducted simulations with a combination of further reclamation and a subsided Yellow River Delta.

[33] The effect of removing the Yellow River Delta on the M_2 tidal amplitude is highly regional (Figure 11). There

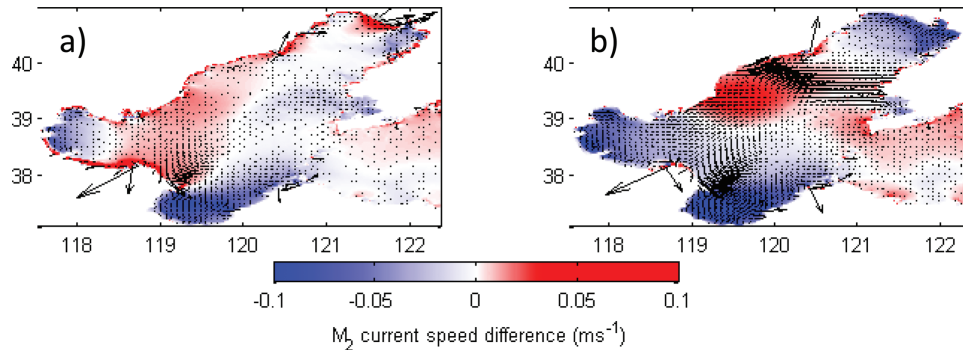


Figure 9. Shown here is the difference in M_2 tidal current speed with the direction and magnitude of the M_2 tidal elevation spatial gradient (arrows) overlain.

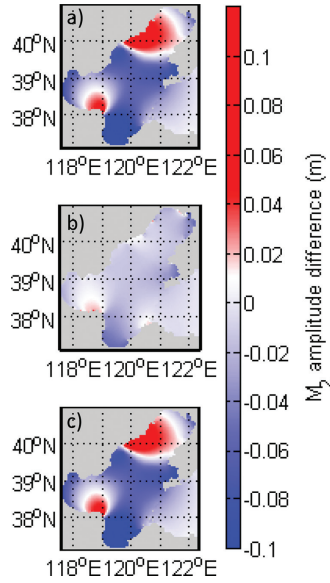


Figure 10. As in Figure 6, but with 2 m SLR applied to the 1976 bathymetry.

is an average decrease in the tidal amplitude of 0.1 m to the north and an increase in the amplitude of 0.05 m to the south of the Delta, respectively. This is because the absence of the Delta allows the tide to travel around the Laizhou, without obstruction and sheltering by the Delta of the area to the south of it.

[34] The continued land reclamation case generates some 200 new ocean cells in the Bohai Bay and sees an overall increase of the M_2 amplitude of 0.02 m within the Bay. However, these changes are concentrated to the north of the area and thus slightly different from the previous trend in the tides over the last 35 years, which while positive, is concentrated to the south of the Bohai Bay. There is a very small decrease throughout the rest of the Bohai Sea,

but this is most likely not significant and will not be discussed further.

[35] Surprisingly, the combination of the removal of the Yellow River Delta and further land reclamation leads to some small, but far field, changes not seen in the individual simulations. There is now a small increase of the M_2 tidal amplitude in the north of Liaodong Bay, but more importantly the enhancement of the tidal elevations in the north of the Bohai Bay seen in the continued land reclamation simulation on its own is now stronger and reaches further around the Bay than previously. This is most likely a back effect of the removal of the delta.

[36] Simulations were also conducted for these scenarios with a future SLR implemented, but there is very little difference between these runs and the SLR simulations described previously, and they are not commented on further.

4. Summary and Discussion

[37] It is shown using a numerical tidal model that rapid coastal development, both natural and anthropogenic, has resulted in significant changes in the tidal dynamics of the Bohai Sea, with the M_2 tidal amplitudes having changed with up to 0.2 m over the last three decades. This could increase the occurrence of flooding, and the associated changes in tidal currents could have changed the sediment transport capacity of the area. These results highlight the sensitivity of regional tides to changes in coastal bathymetry and show that a carefully configured 2-D tidal model can qualitatively and quantitatively reproduce these tidal regimes. The changes in bathymetry between 1976 and 2002 only induced a change in average water depth of some 0.16 m over the domain, but this still had a significant effect on the tides. This relatively small change in depth (although being a net sea level decrease here) is of the same magnitude as that predicted for future global SLR over the present century. Both observations and the model

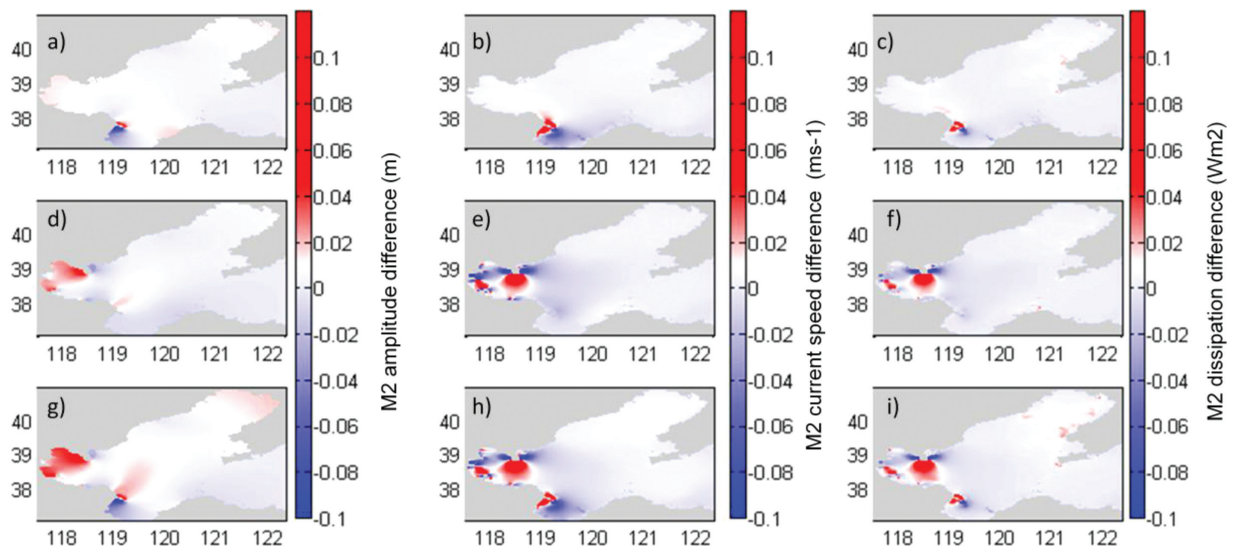


Figure 11. Impact of removal of the (a–c) Yellow River Delta, (d–f) continued land reclamation, and (g–i) a combination of both on the M_2 amplitude (Figures 11a, 11d, and 11g), tidal current speeds (Figures 11b, 11e, and 11h), and tidal energy dissipation (Figures 11c, 11f, and 11i).

capture the changes in the tides and they agree, qualitatively. This adds confidence to our ability to predicting the effect of realistic SLR and other costal bathymetric changes on coastal tidal regimes. Furthermore, the model points to a typical annual rate of M_2 amplitude change in the Bohai Sea on the scale of millimeters per year: the large amplitude increase of 0.2 m in western Laizhou Bay between the 1976 and 2002 simulations, which has support in observations, corresponds to an average rate of 7.7 mm yr^{-1} . This is comparable to the global mean rate of the eustatic sea-level rise of $0.18\text{--}0.79 \text{ mm yr}^{-1}$ [Meehl et al., 2007]. This shows the necessity of taking changes in tidal amplitudes into account when evaluating the interannual variability of high tide levels.

[38] Our results also show that the Bohai Sea is sensitive to further changes, e.g., SLR, further land reclamation and erosion of the Yellow River Delta. There is also a suggested strong sensitivity of the tides in the Bohai Sea to how flood defenses are implemented, but the areas that are protected in the partial flood scenario are not at risk of flooding (based on the bathymetry and levels of SLR used).

[39] The impact of future coastline development, including the subsiding Yellow River Delta, on the dynamics of the Bohai Sea is suggested to be significant, but at the same time confined to the bays where the coastline changes occur. That said, the response of the tides to our future scenarios is not straightforward. For example, in Bohai Bay, there is a spatially complex pattern of increasing and decreasing current speed and associated tidal energy dissipation levels, and it is possible that this could have effects on the small-scale tidal sediment dynamics. However, a further evaluation of this is outside of the scope of this paper.

[40] In this study, we have not changed the boundary conditions in the Yellow Sea. It is possible that the tides in the Yellow Sea have changed between 1976 and 2011, because the area has also experienced large coastline modifications over this period of time. For example, Lee et al. [2008] estimated amplitude changes caused by the construction of a 33 km long dyke along the west coast of Korea and found that M_2 amplitudes may have increased for more than 0.03 m in the south western Yellow Sea when the dyke was completed in 2006. In addition, amplitude changes in the ocean tides may also have modulated the tidal regime in the Bohai Sea by changing the boundary conditions [see Woodworth, 2010]. Nevertheless, this study suggests that the observed tidal change in the Bohai Sea can be explained, at least to some extent, by local changes in bathymetric configurations. Other candidates include variations in stratification [Müller, 2012], which in the Yellow and East China Sea induce a seasonal variation in M_2 amplitude of up 0.2 m. However, more detailed investigations of the impact in the Bohai of the monsoon are left for a future study. It is also possible that higher resolution simulations (both spatial and more bathymetric “time slices”) may improve the fit between model and observations.

[41] One important outcome of this project is highlighting the danger of merging tidal databases from multiple years. Because of the large decadal changes in the Bohai Sea, it is suggested that observations before and after 1976–2002 should be treated separately. Rapid changes in tidal amplitudes are also observed at tide-gauge stations in

other parts of the world. For example, the M_2 amplitude at Cananéia tide gauge station in Southeast Brazil has increased some $0.4\text{--}0.5 \text{ cm decade}^{-1}$ [Harari et al., 2007], which may be linked to an observed SLR of some 4 cm decade^{-1} at the same station. This strongly implies that the increase in water depth or associated bathymetric changes is responsible for this variation in M_2 amplitudes at Cananéia tide gauge station.

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